A STUDY OF THE COMBINED EFFECT OF SOIL MOISTURE AND SEASONAL RAINFALL UPON WHEAT YIELDS ON WESTERN KANSAS FARMS

by

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INTRODUCTION

Thirty four years ago, Failyer (1906) observed that in several of the western states many farmers raised a wheat crop once in two years, storing up water in alternate years. Where rainfall was somewhat greater, a crop was grown two out of three years. In his opinion the system seemed perfectly flexible and should be adopted quite generally in semi-arid regions. His advice to farmers was, "If at seeding time the soil is in a moist condition to a considerable depth, put the crop in, even if a crop was grown on the same ground the preceding season. If sufficient moisture has not been stored in the soil, let the land lie over and continue the tillage. The work on the whole will be less than if a crop be attempted each year and the crop will be greater. Indeed by saving the rainfall of one year to help out the next year, a profitable crop will often be secured when there would have been nothing had an attempt been made to grow a crop each year. ... Where the rains largely come in the winter there is little trouble to conserve moisture sufficient to produce a crop of winter wheat. In the Plains region it is more difficult, for the falls and winters are the dry portion of the year. If there be a deep moist seedbed in the fall, the crop will generally succeed by the aid of spring and early summer rains, but if the condition of the soil is not right, do not attempt a fall crop. Let the land lie over and grow a spring crop or cultivate during the next summer and seed to fall wheat."

That moisture is the primary limiting factor in crop production in western Kansas is so well known that such a fact needs little comment. A problem confronting farmers of that region nearly every fall is whether conditions are such as to warrant seeding of wheat. Some seasons are quite favorable for crop production while many other seasons are extremely dry. The average annual rainfall varies from about 15 inches in the far western counties to slightly more than 20 inches in the central western area. However, the precipitation in any one year may be extremely low, sometimes less than 50 percent of the average. Furthermore, less than average rainfall is received in about two-thirds of the years. Data from the Colby and the Garden City branch experiment stations (Mathews and Brown, 1938) reveal that no paying yield of wheat has been obtained from the use of less than 10 inches of water and that no yield of as much as 20 bushels per acre has been obtained from less than 14 inches. The water used refers to the available water in the soil at seeding time plus the rainfall between seeding and harvest.

Under such conditions it is obviously essential that some moisture be stored in the soil before the crop is seeded if a reasonably satisfactory crop is to be expected with a fair degree of certainty. That there is a relation between the moisture in the soil at seeding time and the yield of winter wheat was shown by Call and Hallsted (1915). This fundamental fact was further developed by Hallsted and Coles (1930) at which time they concluded that a moisture content of 20 percent or more in the upper 3 feet of soil at seeding time at Hays would practically preclude a crop failure as a result of drought.

While it is not a difficult task to determine the percentage of moisture in the soil, it does require some semi-technical ability and equipment with which many farmers are not provided. With this in mind, Hallsted and Mathews (1936) expressed the quantity of soil moisture at seeding time in terms of depth of penetration. The depth to which moisture had penetrated a dry soil was easily observed, the change from wet to dry taking place within a very short vertical distance. They expressed the probabilities of obtaining certain specified yields of wheat on the experiment stations when the soil was wet to designated depths at seeding time.

However, Cole and Mathews (1923) found little correlation between the quantity of stored water used and the yield of spring wheat. They concluded that the quantity of water stored in the soil is never enough to produce a good yield and that the reduction of soil water content by the wheat depends upon sufficiency or insufficiency of rainfall.

At Hays (Hallsted and Mathews, 1936) an average of 26 years shows the normal precipitation from October 1 to May 31 (the wheat growing period) to be 10.26 inches. At Garden City the average of 22 years for the period mentioned is 8.86 inches. Yet, in the 1936-37 wheat growing season (October 1 to May 31) precipitation at Hays was 6.77 inches and at Garden City 4.73 inches and wheat failed even on fields where the soil moisture content at seeding time indicated there should have been a fair yield produced.

The true value of technical research in agriculture is measured by the contribution which that work makes toward agricultural science. The purpose of this study was: first, to test the applicability to Kansas farms of the practice of estimating the chance for a wheat crop from the depth of moisture in the soil at wheat seeding time; and second, to determine the value of subsequent rainfall on fields wet to varying depths at seeding time and to construct a simple formula or equation of estimate of wheat yield based upon two rather easily measurable factors, the depth of moisture in the soil at seeding time and the rainfall during the growing period.

REVIEW OF LITERATURE

Storage of Moisture in the Soil

In regions receiving less than 20 inches average annual rainfall, Failyer (1906) found that it was only in exceptionally wet seasons that dry soil could not be found at a depth of three or four feet. Burr (1914) observed that one inch of water would wet the silt loam soil, at North Platte, Nebraska, to a depth of about six inches and Hallsted and Mathews (1936) found that in 23 years, the silty clay loam at the Hays Experiment Station had not contained more than 6 inches of available water in the upper 3 feet.

The work of Finnell (1929a) in Oklahoma indicated that 20 percent of the normal precipitation was saved for crop growth. Bracken and Cardon (1935) concluded that at Nephi, Utah, approximately 30 percent of the rainfall during a fallow and crop growing period was saved while Barnes (1938) found that summer fallow at Swift Current, Canada resulted in an average conservation of 29.1 percent of the precipitation.

The amount of water stored in the soil was found by Burr (1914) to be dependent upon widely varying factors. Results varied with the amount and distribution of the rainfall during the period of fallow. In years of normal rainfall and with normal distribution the soil at North Platte, Nebraska was filled with water to depths of from five to seven feet. In the driest years, with a lower total precipitation, many isolated rains and light showers, the best methods of tillage resulted in very little water storage. During heavy, torrential rains, water fell so rapidly that it did not have time to penetrate into the soil but rather puddled the surface, rendering it nearly impervious. The type of rain that was most beneficial came slowly enough to be readily absorbed. According to Mathews and Brown (1938) results at Colby and Garden City indicated that when the precipitation from October 1 to September 30 was 10.4 inches or less, no moisture was stored in the fallowed soil. However, for each inch of precipitation in excess of that amount 0.6 inch of water was stored. This relationship prevailed until the soil held 7 inches of available moisture.

Another factor presented by Burr (1914) was the amount of water already present in the soil when the rain fell. Soil which was hard, dry and smooth at the surface absorbed less water than a cultivated soil. The more open the surface, the greater the quantity of water it would admit. The nature of the soil profile was also declared to affect the efficiency with which moisture could be conserved. A shallow soil, underlain with hard-pan, gravel, rock or sheet water was of little value in storing moisture. Mathews and Brown (1938) found the subsoil at Amarillo, Texas to be so heavy that when water penetrated to depths lower than three feet, it was recovered by crop roots only with great difficulty.

Relationship of Soil Moisture to Wheat Yields

The findings of Call and Hallsted (1915) substantiated the observations of Failyer. Since the major part of the rainfall in western Kansas comes during the summer months, they contended that it was necessary to use methods by which the summer rainfall could be stored for the growth of the wheat during late fall and early spring. From an average of four years' results, they learned that every time the amount of available moisture stored in soil was doubled, the yield of winter wheat was approximately doubled. Hallsted and Coles (1930) concluded that a moisture content of 20 percent or more in the upper 3 feet of soil at seeding time at Hays practically precluded a crop failure as a result of drought. With a soil moisture content of much less than 20 percent in the surface 3 feet at seeding time, the chances of securing a large crop were much less and the chances for harvesting a small crop or having a failure were measurably increased. They expressed the relationship of soil moisture at seeding to yield of winter wheat with the regression equation, $Y = 3.12X - 42.2$ where wheat was grown immediately following wheat. When wheat was seeded on fallowed land the relationship of yield to moisture became $Y = 2.51X - 33.91$. (X = percentage of moisture in soil). Burr (1914) found that winter wheat on fallowed land at North Platte, Nebraska varied in yield from 12 bushels to 60 bushels per acre, depending upon the amount of water stored in the soil, the seasonal rainfall and other climatic conditions. In forecasting the yield of winter wheat Henney (1932) discovered that rainfall for the period August to October, combined with spring precipitation one year previous to harvest, had more influence on production than rainfall in the former period alone or precipitation in the spring just previous to harvest. The correlation coefficient of August to October rainfall and yield was $.7914 \pm .0673$ while the coefficient of correlation for rainfall during the spring a year before harvest plus rainfall August 1 to October 31 was $.9272 \pm .0252$.

Hallsted and Mathews (1936) found a definite relationship between the inches of available water in the soil at seeding time and the yield of winter wheat in western Kansas. At Hays there were 27 cases where the soil contained less than 1.5 inches of available water. In 20 of these, yields of less than 10 bushels per acre were produced, 8 being complete failures. In 6 cases yields ranged from 10 to 19 bushels per acre and in 1 case a yield of 20 bushels per acre was obtained. Of 29 cases where 1.5 to 2.9 inches of available water were present at seeding, 12 produced yields of less than 10 bushels per acre; 8 produced 10 to 19 bushels per acre; 6 yielded 20 to 29 bushels per acre; and 2 yielded 30 or more. With 3 or more inches of available water present at seeding time the yield did not fall below 10 bushels per acre and only 4 of the 34 cases were below 20 bushels. Yields from 20 to 29 bushels per acre were harvested in 22 cases, 3 of them ranging from 30 to 39 bushels and 5 exceeding 39 bushels per acre. All yields of 40 bushels or more were obtained where the soil contained an excess of 5 inches of available water at seeding time.

Of 29 cases when the available water content of the soil at seeding time was less than 1.5 inches at Colby, Hallsted and Mathews (1936) found 20 yields of less than 10 bushels per acre, 5 from 10 to 19 bushels and only 4 yields of 20 bushels or more. There were 12 cases where the yield was 3 bushels or less. Of 8 cases when the quantity of available water at seeding ranged from 1.5 to 2.9 inches, 1 was a total failure, 4 produced less than 10 bushels per acre, 2 fell between 10 and 19 bushels and 1 exceeded 20 bushels per acre. Three or more inches of available water were present in 20 cases. In this group, 5 yielded less than 10 bushels, 6 yields fell between 10 and 19 bushels, 4 produced 20 to 29 bushels per acre and 5 yielded 30 bushels or more.

At Garden City there were 24 cases when the available water content at seeding time was less than 1.5 inches. Of these, 17 yielded less than 10 bushels per acre, 5 produced yields of from 10 to 19 bushels and 2 exceeded 19 bushels per acre. There were only 2 cases when the available water content at seeding time was from 1.5 to 2.9 inches. In 1 case the yield fell below 10 bushels and in the other it exceeded 10 bushels per acre. Of 13 cases when 3 or more inches of available water were present at seeding time, 4 yielded less than 10 bushels per acre, 2 ranged from 10 to 19 bushels, 6 fell between 20 and 29 bushels and 1 yielded more than 30 bushels per acre.

According to Hallsted (1937) wheat yields in western Kansas have sometimes been reduced by other factors such as insects and plant diseases, but over a period of years, moisture has been the limiting factor. The hazard of drought was almost always reduced in proportion to the amount of water that was stored in the soil previous to seeding. Stephens (1939) found that where subsoil moisture was below

9 percent in the early spring, poorly tilled plots at Moro, Oregon yielded slightly more wheat than thoroughly tilled plots but that with an increased supply of moisture in the subsoil, the good tillage plots significantly outyielded the poor tillage plots.

To the contrary, Finnell (1929b) declared that in western Oklahoma, the correlation between initial moisture and yields of winter wheat was not at all significant and Burr (1914) observed that with an abundance of moisture in the soil at seeding time more growth was sometimes started than could be supported throughout the entire season.

The relationship of soil moisture to yields of spring wheat has not been so extensively investigated, although Meek (1923) observed that crop failure with spring wheat was sometimes the result of a preceding year of drought.

In a recent study, Cole and Mathews (1940) have suggested that there are occasional years when the precipitation and other factors are such that good yields are produced regardless of the initial water content of the soil. Likewise, in some years, conditions during the growing season may be so unfavorable that only failures or low yields are realized, regardless of the initial moisture content of the soil. They found a positive relationship between the moisture content of the soil at seeding time and the yield of spring wheat.

Influence of Depth of Moisture upon Wheat Yields

More than twenty years ago, Alway, McDole and Trumbull (1918) attempted to estimate the amount of moisture in western Nebraska soil by observation. The success of this attempt is indicated by the fact that in only 3 percent of the samples which they termed "powder," was the ratio of moisture content to hygroscopic coefficient as great as 1.5. Among 163 samples termed "moist," 95 percent possessed a ratio of moisture to hygroscopic coefficient of 1.5 or higher. In the group of 159 samples termed "intermediate," there were 44 percent with ratios as great as 1.5. On the basis of these trials they contended that it could be determined by observation whether the moisture content of a soil was appreciably above or below the wilting coefficient. According to Mathews (1923) the minimum point of exhaustion is considerably lower than the wilting coefficient and soil, when at or near the minimum point, can be recognized as dry. He suggested, however, that an experimental error in sampling existed depending largely upon the lack of uniformity of the soil.

Before considering the relationship of depth of soil moisture penetration to yield of wheat it is desirable to have some knowledge of the depth to which wheat roots normally develop in the soil. Hallsted (1937) observed that at the Fort Hays station in 1935, only 1 plot out of 300 yielded as much as 5 bushels per acre. This plot had been fallowed for three years and was wet to a depth of ten feet at seeding time. Wheat roots used moisture from a depth of nine feet. Upon other occasions Hallsted (1937) has found wheat roots using moisture from the soil to depths of eight or nine feet. When plenty of moisture was available to them, wheat roots were commonly found feeding in the fourth, fifth and sixth foot sections.

Burr (1914) found winter wheat roots to a depth of six or seven feet at North Platte Nebraska.

Investigations with spring wheat by Mathews (1923) indicated the natural zone of root development to be the first four feet of soil. He found that development of any considerable number of roots in the fifth and sixth foot sections of soil was associated with drought. The quantity of moisture held in the fifth and sixth foot sections of soil was usually small and its complete or nearly complete utilization, necessitated conditions so severe that the yield of the crop was almost always seriously compromised.

Mathews (1923) concluded that the utilization of a large soil mass was not essential to a high yield. The yield depended more upon the maintenance of a constant supply of available moisture to the depth at which it could be easily obtained than upon the mass of soil involved.

Hallsted and Mathews (1936) expressed in percentage the probabilities of obtaining specified yields of wheat when the soil was dry or was wet to designated depths at seeding time. Their calculations were based upon results obtained at the Hays, Colby and Garden City dry land experiment stations. Soil that was dry at seeding time produced 4 bushels or less wheat per acre 71 percent of the time and 10 bushels or more 18 percent of the time, but in no case was a yield as high as 20 bushels per acre produced.

Soil wet 1 foot deep at seeding time produced 4 bushels or less 34 percent of the time, 10 bushels or more 43 percent of the time, and 20 bushels or more per acre 19 percent of the time. No yield of as much as 30 bushels per acre was obtained unless the soil was wet deeper than 1 foot.

Moisture penetration of 2 feet reduced the failures to 15 percent, and increased the frequency of yields of 10 bushels or more to 62 percent. In 29 percent of these cases 20 or more bushels per acre were produced and in 9 percent of the cases the yield was 30 bushels or higher.

Only 10 percent were failures when the soil was wet 3 feet or deeper at seeding time; 84 percent yielded 10 bushels or more; 70 percent, 20 bushels or more; and 23 percent made 30 or more bushels of wheat per acre.

Recent studies by Cole and Mathews (1940) showed that the average yield of spring wheat from 178 plots wet 1 foot or less at seeding time, was 6.5 bushels per acre. Two hundred and sixty-two plots wet two feet yielded an average of 11.9 bushels, and 325 plots were wet 3 feet or deeper and produced an average yield of 18.2 bushels per acre.

Rainfall and Wheat Yields

Although Call and Hallsted (1915) found a positive relationship between the amount of available moisture in the soil at seeding time and the yield of winter wheat, their investigations also revealed that a certain amount of stored moisture did not insure a certain yield of wheat. The yield secured was quite as dependent upon the amount and distribution of rainfall during the growing season. Cole and Mathews (1923) observed a similar situation in connection with the growing of spring wheat and Mathews (1925) found it practically impossible to predict yields of spring wheat accurately early in the season because the rainfall during the growing period was seldom normal. He did suggest, however, that as the season developed, the yield could be foretold with increasing accuracy. Finnell (1929b) found a high degree of relationship between seasonal rainfall and yield of winter wheat and Daniel (1935), continuing the work of Finnell, pointed out that from 1925 to 1934 at Goodwell, Oklahoma no wheat was produced when less than 15 inches of rain fell during the growing season and when the seasonal evaporation exceeded 70 inches. Recent work by Hallsted and Mathews (1936) tends to minimize the effect of rainfall during the growing period at Hays, Kansas. Of 49 cases at Hays when the amount of water in the soil at seeding time was below average, 41 produced below average yields in spite of the fact that precipitation during the life of the crop was above average in 26 instances. Above average rainfall, after the crop was planted, increased the yield to above average in only one-third of the cases in which it occurred. On the other hand, when the water content of the soil at seeding time was above average, precipitation below average during the growing period resulted in below average yields in only one-fifth of the cases in which it occurred. However, above normal rainfall during the wheat growing period at Colby and at Garden City made up for a deficiency at seeding in nearly half of the years in which it occurred.

Fisher (1925) stated that the average effect of additional rainfall was harmful to winter wheat yields in the humid climate at Rothamsted, England but the effect per inch of rainfall in October was small or often beneficial. The autumn period of benefit or but little loss, from rain, was followed by a period centered in January in which dry conditions appeared to be particularly beneficial. At that time of year, each additional inch of rain cost from one to two bushels of crop yield per acre. Likewise, in the eastern part of Kansas, where rainfall is more abundant, low yields of wheat are probable in years of high spring rainfall.[1]

Above average rainfall has been associated with higher yields of spring wheat in Canada but the maximum influence was exerted by precipitation during the month of June, according to Hopkins (1933-34) who found (1935) that wheat on fertile soil received the maximum benefit from additional rain approximately at tillering time. On less fertile soil the maximum benefit occurred somewhat earlier. Hopkins' work (1935) demonstrated that wheat on fallowed plots was able to use later rains more advantageously because early moisture needs were usually met by greater reserves in the soil. His findings agreed with Fisher (1925) and Laude[2] (1937) in that on fertile soil, additional rainfall near maturity often resulted in lower yields.

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[1] Laude, H. H. Soil moisture and nutrients in relation to yield of winter wheat. (Farm and Home Week Address, 1937)

[2] Loc. cit.

Smith (1925) found a correlation of 0.868 $\pm$ 0.056 between average rainfall from mid-May to mid-July and the yield of spring wheat at Dickinson, North Dakota, but Bracken and Cardon (1935) were unable to find a significant correlation between spring precipitation and yield of winter wheat at Nephi, Utah.

Davis and Pallesen (1940) in discussing the effect of seasonal rainfall on spring wheat yields, stated that the greatest beneficial effect is from rain that comes during the rapid growing period of the plant, reaching a maximum about three weeks before average heading date. They found an increase of about four bushels per acre for each additional inch of rainfall at that time in the season. The effect of additional rain rapidly diminished from the time of heading.

Pallesen and Laude, in an unpublished manuscript, have extended a similar study to winter wheat in western Kansas.[3] They have pointed out that rainfall is of greatest advantage to winter wheat prior to and during the period from seeding to the time the wheat enters the winter semi-dormant stage; or during germination, emergence, tillering and root development. The benefit of an extra inch of rainfall was

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[3] Pallesen, J. E. and Laude, H. H. Seasonal distribution of rainfall in relation to yield of winter wheat. (Manuscript in process of preparation for publication), Agron. Dept., Kans. Agr. Expt. Sta. 1940.

about three bushels of wheat per acre. Their findings agreed with those of Hopkins (1935) in that the influence was greater on the continuously cropped than on the fallow plots. They also pointed out the slight consequence of rainfall during late winter and the adverse effect of above normal early spring precipitation. A second, but less important, period of beneficial effect of above average rainfall was discovered during the period of rapid stem growth and heading.

Correlation Between Water Used and Yield

The amount of water required for a small cereal crop in semi-arid sections is about 500 tons of water to 1 ton of crop produced, according to Shantz (1925).

Barnes (1938) found that wheat grown on summer fallow required 1350 pounds of water for each pound of threshed grain and wheat on stubble land, 2000 pounds of water for each pound of threshed grain.

The quantity of water used during periods of the same length was nearly the same, concluded Cole and Mathews (1923), no matter whether the use was largely precipitation for that period or whether it represented water stored in the soil. The minimum varied from about 4 inches at northern stations to 10 inches at southern stations. In the dry land area, Cole and Mathews (1923) found spring wheat would use 0.15 to 0.20 inch of water per day in the Northern Plains and 50 percent to 60 percent more in the Southern Plains. Knowing the daily rate of use of water and the time necessary to mature a crop; or the total quantity of water required for a given production, the probable yield from a given precipitation during the remainder of the growing season or the precipitation necessary to produce a given yield could be calculated, they said.

From the records at the Colby Experiment Station, Mathews and Brown (1938) found that no paying yield of wheat was obtained from the use of less than 10 inches of water. They expressed the relationship of yield to water used by the equation, yield $= \frac{\text{water used} - 7.13}{0.53}$. The correlation between yield and total water used was 0.70 ± 0.049. An equation based upon Garden City records was very similar to the one arrived at for Colby and the combined data from the two stations provided the following, yield $= \frac{\text{water used} - 7.37}{0.51}$. The combined correlation coefficient was 0.749 ± 0.033. The relationship was not, however, a straight line regression throughout. Estimated yields were too high for quantities of water less than 10 inches. Likewise, Alsberg and Griffing (1928) stated that the relationship of environment and crop yield often are not merely linear but there are also limits beyond which no crop is possible. They contended that the wheat crop must fail if at certain stages of its growth there is not a certain minimum of soil moisture available. "There is a threshold value for moisture," they said, "which must be attained to make any growth possible." These investigators observed that a given increment in moisture must produce quite a different response according as the quantity to which it is added is above, at, or below threshold value. If below the threshold value, this increment could have an effect only if it is large enough to raise the total above the threshold value. Even a large increment might, therefore, have no effect at all.

With increasing increments the effects become larger and then decrease until near the optimum they exert little effect. Therefore, concluded Alsberg and Griffing (1928) relations between environmental factors and yield are not universally linear. These men suggested that to use years of failure with the years in which rainfall exceeded the threshold value would result in obscuring the real correlations that exist. Furthermore, they propose the abandonment of data in years in which a crop failure or great reduction in yield came about because of some catastrophe like hail or hurricane, and not in any way because of the particular factor being correlated with yield.

Mathews (1925) pointed out that both the initial requirement, or threshold, and the quantity of water necessary for each additional bushel of yield vary with the climate and are higher as one goes from north to south in the Great Plains, except as the distance south is modified by altitude.

After observing the relationship of rainfall to wheat yield, Henney (1932) suggested that different parts of Kansas would need separate, individual estimating equations in order for such equations to be of practical value for forecasting. Consequently, his studies (1935) were based upon crop reporting districts although he recognized the possibility of using type-of-farming areas.

MATERIAL AND METHODS

Accumulation and Organization of Data

Almost simultaneously with the publication of the work of Hallsted and Mathews (1936) expressing the relationship of depth of moisture at seeding time and yields of winter wheat, a conservative program was launched among farmers of western Kansas for the purpose of testing the applicability to Kansas farms of the practice of estimating the chance for a wheat crop from the depth of moisture in the soil at seeding time. The collection of data was made possible through the assistance of county agricultural agents who in turn enlisted the cooperation of reliable farmers in each county. Cooperating farmers and county agents were encouraged to determine the depth to which the soil was wet at seeding time, by digging down in the soil of fields prepared for wheat. The area studied included the territory west of a line drawn from the southeast corner of Barber county to the northeast corner of Smith county.

Since only a few cooperators were equipped with regular soil sampling equipment, implements used in making depth of moisture observations varied from ordinary spades, posthole diggers and similar crude equipment to augers and soil tubes made expressly for the purpose. Naturally, there was some disagreement as to when soil was wet or dry. Some could feel moisture in soil that others would insist was dry. This variation in judgment was recognized as a source of error. If such a relationship were to have any practical application on individual farms generally the correlation would have to be close enough to offset such errors since few farmers would be sufficiently trained to make extremely accurate readings. However, it was suggested to county agents and farmers that soil so nearly dry as to cause the person making the observation to question its condition, be designated as dry and only soil unquestionably containing available moisture be designated wet. That recommendation, it is believed, helped to eliminate part of the sampling error.

County agricultural agents were supplied with duplicate copies of uniform report blanks for use in recording the observations of cooperating farmers (Form 1). Each report form contained space for recording names of cooperators, the depth of moisture penetration at seeding time and the yield of wheat per acre. Separate columns were provided in which to record data from fallowed fields, continuously cropped or check fields, fields planted to wheat the second, third or fourth consecutive year since having been fallowed, and a column for remarks in which to note poor tillage, hail damage, wind damage or other factors which might lend a peculiar influence toward the results. Copies of reports were assembled and edited after the wheat was seeded. Edited copies of each county report were prepared in duplicate, one copy being retained and the other returned to the county agent for his use in recording and reporting yield data at harvest time.

The spread of the work over the area developed rather slowly in the beginning. In the first year, 1936, data including depth of moisture at seeding time and yield of wheat harvested were obtained on only 178 fields. However, the project gained impetus in 1937 when reports were obtained

Form 1. Depth of Soil Moisture at Wheat Seeding Time and Yield of Wheat.

Clark County 1936 Year

Name	Address	Wheat after fallow		Check field		1st year wheat after wheat		2nd year wheat after wheat		3rd year wheat after wheat		Remarks
		Moisture	Yield bu. per A	Moisture	Yield bu. per A	Moisture	Yield bu. per A	Moisture	Yield bu. per A	Moisture	Yield bu. per A	
J. V. Crane	Ashland	40"	18	12"	6							
J. E. Bell	Bucklin	36"	14	8"	4							
Ray Cleaver	Ashland					8"	3					
Geo. Abell	Ashland					8"	0					
W. T. Moore	Ashland							8"	0			
L. C. McInteer	Minneola							7"	3			
H. W. Estes	Sitka									6"	3	
Chas. Haller	Bucklin									5"	0	

from 701 fields. In 1938, reports were obtained from 1,572 fields so that paired data were recorded on a total of 2,451 fields in the three years. Years referred to are harvest years. For example, depth of moisture data for 1936 were gathered at wheat seeding time in the fall of 1935.

Reports from 473 fields in 1939 were not included in the original analyses but were retained as independent data for the purpose of testing the equation of estimate derived from the study of earlier data.

Information as to the rainfall during the wheat growing period was secured from reports of the United States Weather Bureau (Flora, 1935, 1936, 1937, and 1938) for the counties comprising the area studied. Some error was inevitable because it may not necessarily rain on a particular farm field at the same time or in the same amount that it rains at the official weather observation point. However, this irregularity was perhaps partially overcome by grouping the individual data into type-of-farming areas (Throckmorton, Hodges, Pine, and Grimes, 1937). Thus, there were as many rainfall samples per type-of-farming area as there were counties included in the area.

For the purpose of this research, the wheat growing period was defined as October 1 to May 31. Such an arbitrary definition is somewhat inaccurate and consequently is the source of some additional error because rain may have fallen after the date of seeding, for early planted wheat, and before October 1. Likewise, May 31 does not mark the absolute end of the actual growing period. However, the exact date of seeding was not known for individual fields and, on the other hand, if growing wheat were doomed to failure, it was thought considerable advantage would be gained in being able to recognize such a situation early enough to permit abandonment and subsequent preparation of the soil for a spring crop or for fallow, as suggested by Hallsted and Mathews (1936).

Methods of Analysis

Because one objective of this investigation was to test the practical application of the relationship of soil moisture depth at seeding to the yield of wheat, only those two variates were considered in the beginning. Fields were first classified into groups on the basis of one foot moisture depth intervals and the percentage of the time that yields within specified limits were obtained when the soil was dry at seeding time or was wet to designated depths, was calculated. The class averages of yield from fields grouped on the basis of six-inch moisture depth intervals were also calculated. Regression coefficients for yield on depth of moisture were computed and linear regression lines were plotted for each of the three years and for the combined data from all three years. Methods of computation suggested by Snedecor (1937) were used.

Having studied the linear relationship of depth of soil moisture at seeding and the yield of wheat, a third variate, rainfall during the growing period, was introduced. In order to study the multiple relationship of depth of soil moisture at seeding time, rainfall during the growing period and yield of winter wheat, a statistical analysis was made, using Snedecor's (1937) "Alternative Method of Computation" of multiple regression and covariance.

RESULTS OF STUDY

Relationship of Depth of Soil Moisture at Seeding Time to Yield of Wheat

Some preliminary studies of the relationship of depth of soil moisture at seeding time to yield of winter wheat were made before all of the reports had been received from the cooperators. Data from 2,360 fields were included in this preliminary analysis. When classified into groups on the basis of six-inch moisture depth intervals, these 2,360 fields presented a rather interesting indication of the effect upon wheat yield of varied depths of soil moisture at the time of seeding.

Table 1. The effect of depth of moisture at seeding time upon average yields of wheat. (1936-1937-1938 harvests).

Depth of moisture at seeding time	Number of fields	Average yield of wheat per acre
(Inches)		(Bushels)
0 to 6	163	3.5
7 to 12	321	5.0
13 to 18	380	7.5
19 to 24	421	10.2
25 to 30	316	12.0
30 or deeper	759	14.3

As shown in Table 1, the average yield of wheat increased at the rate of approximately two bushels per acre for each increase of six inches in moisture depth at the time of seeding. The average yield harvested from fields wet down six inches or less was 3.5 bushels per acre. Fields wet 7 to 12 inches deep, produced an average yield of 5.0 bushels per acre; fields wet 13 to 18 inches deep averaged 7.5 bushels per acre; fields wet down 19 to 24 inches yielded an average of 10.2 bushels per acre; a 12 bushel average was reported from fields wet 25 to 30 inches deep and when the soil was wet 31 inches or deeper, the average yield was 14.3 bushels of wheat per acre.

Independent studies of the relationship of depth of moisture and yield on summer fallowed fields and depth of moisture and yield on check fields, or fields cropped continuously, showed that summer fallowing increased the yield of wheat approximately in proportion to the increase in depth of moisture resulting from fallow. In other words, moisture seemed to be the important factor and fallowed soil that was dry at seeding time produced no greater yield, on the average, than continuously cropped soil that was dry when seeded. Likewise, soil wet at seeding time, even though having been cropped the previous year, yielded as satisfactorily as fallowed soil, similarly wet.

Since it was evident, from the data studied, that a positive relationship existed between the depth of soil moisture at seeding time, as determined by farmers, and the yield of wheat harvested, the question arose as to the chances of harvesting a profitable crop from wheat seeded in soil wet to specific depths. Table 2 expresses the times out of 100 that crops within certain specified yield limits were obtained when the soil was dry or was wet to designated depths at the time of seeding.

From a practical standpoint, soil into which moisture has penetrated to a depth of six inches or less probably may as well be called dry soil. The seeding operation will usually result in the drying of the soil to the depth to which it is stirred by the drill and although there may be sufficient moisture present to germinate the seed, unless additional rains come almost immediately the young seedlings will perish.

Table 2. The percentage of times that specified yields of wheat were obtained when the soil was wet to designated depths at seeding time.

Depth of moisture at seeding time (Inches)	Times out of 100 that specified yields of wheat were obtained				
	0 to 5 Bushels	5.1 to 10 Bushels	10.1 to 20 Bushels	20.1 to 30 Bushels	More than 30 Bus.
0 to 6	73	18	8	1	0
7 to 18	49	29	21	1	0
19 to 30	23	23	34	19	1
31 or deeper	12	22	45	18	3

Table 2 shows that 73 percent of the fields that were wet 6 inches or less at seeding time produced 5 or less bushels of wheat per acre. Forty-nine percent of the yields were 5 bushels or less when wheat was seeded in soil wet down 7 to 18 inches but where moisture had been stored to depths of 19 inches to 30 inches, failures were reduced to 23 percent and only 12 percent were failures when the soil was wet down 31 inches or deeper.

Hallsted and Mathews (1936) reported that on the dry land experiment stations in western Kansas, wheat seeded in dry soil produced less than 5 bushels per acre in 71 percent of the cases. Thirty-four percent of the yields were below 5 bushels when the soil was wet 1 foot at seeding. Moisture

2 feet deep reduced failures to 15 percent and only 10 percent of the time did failures occur if the soil was wet into the third foot at seeding time.

Yields of 5.1 bushels to 10 bushels per acre were harvested from 18 percent of the fields which were dry or nearly dry when seeded while only 8 percent of this same group of fields yielded 10.1 to 20 bushels per acre; 1 exceeded 20 bushels but none yielded more than 30 bushels per acre.

When the seedbed was wet from 7 to 18 inches deep, 29 percent of the yields fell between 5.1 and 10 bushels per acre; 21 percent fell between 10.1 and 20 bushels; 1 percent exceeded 20 bushels but none yielded more than 30 bushels per acre.

With moisture into the soil to depths from 19 inches to 30 inches, 23 percent of the yields were between 5.1 and 10 bushels per acre; 34 percent made more than 10 bushels but were not in excess of 20; 19 percent yielded between 20.1 and 30 bushels per acre and 1 percent exceeded 30 bushels per acre.

When the depth of soil moisture was greater than 30 inches at seeding time, 22 percent of the fields yielded from 5.1 bushels to 10 bushels of wheat per acre; 45 percent yielded from 10.1 bushels to 20 bushels; 18 percent of the yields were between 20.1 and 30 bushels and 3 percent exceeded 30 bushels of wheat per acre.

As previously stated, 2,360 pairs of data were included in this preliminary study. Total data studied in the three years, 1936 to 1938, include 2,451 tests. The detailed record including data for each individual test is rather voluminous, hence the data have been condensed in Table 3.

Moisture depth, as recorded in Table 3, is the average depth of moisture in the soil at seeding time for the number of fields studied in each county each year. Rainfall, October 1 to May 31, was obtained from reports of the United States Department of Agriculture Weather Bureau (Flora, 1935, 1936, 1937, and 1938). Yield per acre is the average yield of wheat produced on fields in which the depth of moisture at seeding time was determined.

Type-of-farming areas referred to are the areas described by Throckmorton, Hodges, Pine, and Grimes (1937). Area totals for depth of moisture, rainfall and yield, in Table 3, are summations of individual samples. Area averages are the respective area totals divided by the total number of fields for the area. Thus, for example, there were six fields in Ellis county which were studied in 1936. The average or mean depth of moisture in these fields was 24.5 inches, rainfall October 1 to May 31 was 10.30 inches, and the average yield of wheat, 15.7 bushels per acre. In type-of-farming area 7, of which Ellis county is a part,

Table 3. The number of fields, average moisture depth, rainfall during the growing period and yield of wheat by counties and by type-of-farming areas for individual years and for the total of three years studied.

Type-of-farming area	County	1936				1937				1938				1936-37-38			
		No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre
			Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels
7	Ellis	6	24.5	10.30	15.7	6	40.0	6.77	11.3	21	33.2	15.54	12.2	33	32.9	12.99	12.7
	Osborne									12	28.9	11.47	16.4	12	28.9	11.47	16.4
	Rooks	8	21.8	8.26	11.3	18	22.9	8.10	13.4	72	17.1	12.01	15.5	98	18.5	10.99	14.8
	Russell					15	24.5	8.92	15.4					15	24.5	8.92	15.4
Total		14	321	127.88	184	39	1020	320.22	541	105	2273	1328.70	1573	158	3614	1776.80	2298
Average			22.9	9.13	13.1		26.2	8.21	13.9		21.6	12.65	15.0		22.9	11.25	14.5
8	Norton					20	17.6	5.76	10.3	19	21.6	12.70	13.4	39	19.5	9.14	11.8
	Phillips									20	18.9	12.08	16.0	20	18.9	12.08	15.9
	Smith									7	28.6	10.89	10.9	7	28.6	10.89	10.9
Total						20	351	115.20	205	46	989	559.13	650	66	1340	674.33	855
Average							17.6	5.76	10.3		21.5	12.16	14.1		20.3	10.22	13.0
9	Barton					9	33.6	8.91	14.1	79	28.5	15.81	11.1	88	29.0	15.10	11.4
	Edwards	9	23.3	7.41	9.3	11	28.2	8.79	12.7					20	26.0	8.17	11.2
	Kiowa	11	23.2	9.00	13.6	11	26.3	11.93	11.1	32	31.3	14.31	14.2	54	28.6	12.74	13.4
	Pawnee	8	22.5	8.81	19.3	9	29.2	7.93	13.2	31	28.8	15.50	16.4	48	27.8	12.97	16.3
	Pratt					21	43.4	10.26	21.7	8	40.4	15.89	13.6	29	42.6	11.83	19.5
	Rush	9	19.3	8.22	19.0	9	21.0	7.86	8.3	23	31.1	13.57	21.4	41	26.3	11.14	18.0
	Stafford	16	22.9	8.90	15.3					62	38.7	15.46	16.0	78	35.4	14.11	15.8
Total		53	1185	452.55	803	70	2263	666.10	1039	235	7585	3585.16	3428	358	11033	4703.81	5270
Average			22.4	8.54	15.2		32.3	9.52	14.8		32.3	15.26	14.6		30.8	13.14	14.7

Table 3 continued.

Type-of-farming area	County	1936 No. of fields	1936 Moisture depth	1936 Rainfall Oct. 1 to May 31	1936 Yield per acre	1937 No. of fields	1937 Moisture depth	1937 Rainfall Oct. 1 to May 31	1937 Yield per acre	1938 No. of fields	1938 Moisture depth	1938 Rainfall Oct. 1 to May 31	1938 Yield per acre	1936-37-38 No. of fields	1936-37-38 Moisture depth	1936-37-38 Rainfall Oct. 1 to May 31	1936-37-38 Yield per acre
			Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels
10a	Finney	14	21.4	7.82	2.1	8	28.0	4.73	8.8	35	25.5	7.42	5.8	57	24.8	6.97	5.3
	Hodgeman					15	18.7	6.34	2.5	14	15.9	11.45	4.6	29	17.3	8.81	3.6
	Lane					14	17.9	4.08	3.4	24	17.4	8.78	9.4	38	17.6	7.05	7.2
	Ness					18	24.9	5.61	5.6	47	22.3	11.92	7.8	65	23.0	10.17	7.2
Total		14	300	99.48	30	55	1203	291.04	257	120	2577	1190.96	868	189	4080	1581.48	1155
Average			21.4	7.82	2.1		21.9	5.29	4.7		21.5	9.92	7.2		21.6	8.37	6.1
10b	Ford	26	13.7	9.31	7.6	18	18.1	6.44	2.1	70	15.1	11.68	7.8	114	15.3	10.31	6.8
	Grant	9	12.0	10.57	5.4	24	23.5	4.04	0.6	17	23.1	6.78	4.8	50	21.3	6.15	2.9
	Gray	11	18.3	8.30	5.0	27	28.1	4.80	5.8	68	23.4	9.64	8.3	106	24.0	8.27	7.3
	Haskell					15	27.2	3.93	2.5	33	22.3	7.56	4.0	48	23.8	6.43	3.5
	Meade					12	28.8	5.14	6.7	40	24.9	10.47	8.9	52	25.8	9.24	8.4
	Morton					26	16.4	3.67	0.0					26	16.4	3.67	0.0
	Seward					11	33.5	4.55	8.4	22	29.1	7.28	5.6	33	30.6	6.37	6.5
	Stanton					26	17.4	3.33	0.7	34	30.0	6.75	5.8	60	24.5	5.27	3.6
	Stevens					10	21.5	4.04	0.0	26	23.0	6.60	5.9	36	22.6	5.89	4.3
Total		46	665	428.49	301	169	3865	735.56	436	310	7032	2817.92	2152	525	11562	3981.97	2889
Average			14.5	9.32	6.5		22.9	4.35	2.6		22.7	9.09	6.9		22.0	7.58	5.5
10c	Barber									35	28.3	17.92	13.7	35	28.3	17.92	13.7
	Clark	10	13.8	11.90	5.1	24	16.6	7.14	4.3	143	23.9	15.48	7.7	177	22.4	14.15	7.1
	Comanche	3	23.0	9.84	10.0	29	40.1	8.31	10.1	125	36.6	16.52	14.2	157	37.0	14.88	13.4
Total		13	207	148.52	81	53	1562	412.35	397	303	8984	4905.84	3361	369	10753	5466.71	3839
Average			15.9	11.42	6.2		29.5	7.78	7.5		29.7	16.19	11.1		29.1	14.80	10.4

Table 3 continued.

Type-of-farming area	County	1936				1937				1938				1936-37-38			
		No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre
			Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels		Inches	Inches	Bushels
11	Cheyenne					114	28.6	5.25	10.1	86	28.0	10.99	18.1	200	28.4	7.72	13.6
	Decatur					14	22.9	4.71	5.1	47	22.3	11.17	18.0	61	22.5	9.69	15.0
	Graham	2	10.0	9.88	9.5	16	26.8	4.66	3.8	5	21.6	12.92	19.0	23	24.2	6.91	7.6
	Sheridan	4	16.5	8.18	7.8	20	20.1	5.36	3.8	59	23.7	12.68	12.5	83	22.5	12.83	10.2
	Sherman	8	15.3	6.53	6.1	17	23.2	5.00	5.1	46	22.9	10.46	11.1	71	22.1	8.71	9.1
	Rawlins	9	19.0	6.93	10.7	20	30.2	6.05	7.5	44	29.0	11.94	21.3	73	28.1	9.71	16.2
	Thomas	8	16.5	7.16	8.1	10	46.2	5.81	8.3	24	36.6	9.62	12.8	42	35.0	8.24	10.8
Total		31	511	224.37	260	211	5876	1110.30	1681	311	8168	3697.25	4994	553	14555	5031.92	6935
Average			16.5	7.24	8.4		27.8	5.26	8.0		26.3	11.89	16.1		26.3	9.10	12.5
12	Greeley					16	19.4	3.14	1.4	20	24.2	9.84	8.9	36	22.1	6.86	5.5
	Hamilton									25	26.4	7.04	3.9	25	26.4	7.04	3.9
	Kearny					10	19.6	3.97	5.1	20	27.3	6.45	9.6	30	24.7	5.62	8.1
	Logan					27	23.1	5.00	5.0	13	17.5	12.09	13.3	40	21.3	7.30	7.7
	Scott	5	20.2	9.59	8.4	4	23.3	7.09	10.2	18	29.6	10.22	8.8	27	26.9	9.64	8.9
	Wallace					9	28.0	3.84	0.0	18	27.8	15.19	12.3	27	27.9	11.41	8.2
	Wichita	2	30.0	9.10	17.5	18	23.7	4.72	8.4	28	29.4	10.16	11.9	48	27.3	8.08	10.8
Total		7	161	66.15	77	84	1902	372.82	400	142	3771	1400.83	1351	233	5834	1839.80	1828
Average			23.0	9.45	11.0		22.6	4.44	4.8		26.6	9.87	9.5		25.0	7.90	7.8
All areas	Total	178	3350	1547.44	1736	701	18042	4023.59	4956	1572	41379	19485.79	18377	2451	62771	25056.82	25069
	Average		18.8	8.69	9.8		25.7	5.74	7.1		26.3	12.40	11.7		25.6	10.22	10.2

there were 14 fields studied in 1936. The average moisture depth in these fields was 22.9 inches, average rainfall in the area, 9.13 inches and average yield of wheat 13.1 bushels per acre on the fields studied.

Area totals are included in Table 3 because they were used extensively in the statistical treatment of the data.

For convenience in statistical study of the data, certain symbols have been used to represent variables as follows:

X = depth of moisture at seeding time
X_1 = rainfall October 1 to May 31
Y = yield of wheat per acre
N = number of samples

Summations, or totals, were indicated by preceding a symbol with "S". Thus, SX would represent the summation of moisture depths, SX_1, would be the summation of rainfall values and SY the summation of yields. A bar was placed above symbols for means ($\overline{Y}$ = mean of Y).

Table 4 was constructed from area totals and totals for all areas in Table 3, but, in Table 4, the column headings have been replaced by symbols.

The individual values for depth of moisture, rainfall and yield were totaled by type-of-farming areas, the respective totals squared and recorded in Table 5 as $(SX)^2$, $(SX_1)^2$, and $(SY)^2$. Likewise, the individual values were squared and the squares totaled and recorded as $S(X)^2$, $S(X_1)^2$ and $S(Y)^2$

Table 4. Summations of number of fields, moisture depth at seeding time, rainfall during the growing period and yield of wheat per acre for type-of-farming areas and for all areas by years and for the three years studied.

Area	1936				1937				1938				1936-37-38			
	N	SX	SX_1	SY	N	SX	SX_1	SY	N	SX	SX_1	SY	N	SX	SX_1	SY
7	14	321	127.88	184	39	1020	320.22	541	105	2273	1328.70	1573	158	3614	1776.80	2298
8					20	351	115.20	205	46	989	559.13	650	66	1340	674.33	855
9	53	1185	452.55	803	70	2263	666.10	1039	235	7585	3585.16	3428	358	11033	4703.81	5270
10a	14	300	99.48	30	55	1203	291.04	257	120	2577	1190.96	868	189	4080	1581.48	1155
10b	46	665	428.49	301	169	3865	735.56	436	310	7032	2817.92	2152	525	11562	3981.97	2889
10c	13	207	148.52	81	53	1562	412.35	397	303	8984	4905.84	3361	369	10753	5466.71	3839
11	31	511	224.37	260	211	5876	1110.30	1681	311	8168	3697.25	4994	553	14555	5031.92	6935
12	7	161	66.15	77	84	1902	372.82	400	142	3771	1400.83	1351	233	5834	1839.80	1828
All areas	178	3350	1547.44	1736	701	18042	4023.59	4956	1572	41379	19485.79	18377	2451	62771	25056.82	25069

and products of individual samples were computed, totaled and entered as $S(XX_1)$, $S(XY)$ and $S(X_1Y)$.

The next procedure consisted of dividing the total sums of squares from Table 5 by the corresponding number of fields to determine the correction terms for use in computing deviations of the squares from their respective means.

Likewise, using summations from Table 4, products were obtained and divided by the corresponding number of fields to determine correction terms necessary to compute the deviations of products from the means of products.

Thus, the correction term for the total data (3 years) became:

$$\text{For } X: \frac{(SX)^2}{N} = \frac{3940198441}{2451} = 1607588$$

$$\text{For } X_1: \frac{(SX_1)^2}{N} = \frac{627844228.51}{2451} = 256158.40$$

$$\text{For } Y: \frac{(SY)^2}{N} = \frac{628454761}{2451} = 256407.49$$

$$\text{For } XY: \frac{(SX)(SY)}{N} = \frac{(62771)(25069)}{2451} = 642026.2$$

$$\text{For } X_1Y: \frac{(SX_1)(SY)}{N} = \frac{(25056.82)(25069)}{2451} = 256282.91$$

$$\text{For } X_1X: \frac{(SX_1)(SX)}{N} = \frac{(62771)(25056.82)}{2451} = 641714.26$$

Lower case letters were used to represent deviations from means which were computed as follows:

Table 5. Total sums of squares and products for each type-of-farming area and for all areas (1936-37-38).

Area	N	$(SX)^2$	$(SX_1)^2$	$(SY)^2$	$S(X)^2$	$S(X_1)^2$	$S(Y)^2$	$S(XX_1)$	$S(XY)$	$S(X_1Y)$
7	158	13060996	3157018.24	5280804	106773	20866.46	39604	40526.25	55735	25885.24
8	66	1795600	454720.95	731025	38612	7476.73	14491	13998.40	20237	9100.38
9	358	121727089	22125828.52	27772900	403533	65165.20	99240	147620.37	180782	69803.80
10a	189	16646400	2501078.99	1334025	121002	14728.18	14042	33836.40	33346	10166.34
10b	525	133679844	15856085.08	8346321	350833	35124.06	34451	85312.09	82208	25125.82
10c	369	115627009	29884918.22	14737921	384481	84553.09	55647	114301.84	133001	59108.94
11	553	211848025	25320218.89	48094225	464099	52634.25	130793	138093.31	207264	67798.34
12	233	34035556	3384864.04	3341584	185956	17182.04	25842	47030.28	54419	16797.26
All areas	2451	3940198441	627844228.51	628454761	2055289	297730.01	414110	620718.94	766992	283786.12

Total sums of squares:

$$Sx^2 = 2055289 - 1607588 = 447701$$

$$Sx_1^2 = 297730.01 - 256158.40 = 41571.61$$

$$Sy^2 = 414110 - 256407.49 = 157702.51$$

Total sums of products:

$$Sxy = 766992 - 642026.2 = 124965.80$$

$$Sx_1y = 283786.12 - 256282.91 = 27503.21$$

$$Sxx_1 = 620718.94 - 641714.26 = -20995$$

Sums of squares of area means:

$$\begin{aligned} Sx^2 &= \frac{(3614)^2}{158} + ------ + \frac{(5834)^2}{233} - 1607588 \\ &= 82664.53 + 27206.06 + 340019.80 + 88076.19 \\ &+ 254628.27 + 313352.32 + 383088.65 + 146075.35 \\ &- 1607588 = 27523.17 \end{aligned}$$

$$\begin{aligned} Sx_1^2 &= 19981.13 + 6889.71 + 61803.99 + 13233.22 \\ &+ 30202.06 + 80988.94 + 45787.01 + 14527.31 \\ &- 256158.40 = 17254.97 \end{aligned}$$

$$\begin{aligned} Sy^2 &= 33422.81 + 11076.14 + 77577.93 + 7058.33 \\ &+ 15897.75 + 39940.16 + 86969.67 + 14341.56 \\ &- 256407.49 = 28876.86 \end{aligned}$$

Sum of products of areas:

$$\begin{aligned} Sxy &= \frac{(3614)(2298)}{158} + ----- + \frac{(5834)(1828)}{233} \\ &- 642026.2 = 52563.11 + 17359.09 + 162413.16 \\ &+ 24933.33 + 63624.03 + 111872.00 + 182529.70 \\ &+ 45770.61 - 642026.2 = 19038.83 \end{aligned}$$

$$\begin{aligned} Sx_1y &= 25842.32 + 8735.64 + 69243.24 + 9664.60 \\ &+ 21912.21 + 56874.52 + 63103.73 + 14434.14 \\ &- 256282.91 = 13527.49 \end{aligned}$$

$$\begin{aligned} Sx_1x &= 40641.49 + 13690.94 + 144964.06 + 34139.89 \\ &+ 87694.36 + 159304.97 + 132440.50 + 46066.07 \\ &- 641714.26 = 17227.97 \end{aligned}$$

Regression of Yield on Depth of Moisture at Seeding Time

The total sums of squares and sums of products and the area sums of squares and sums of products obtained in the manner described were entered in Table 6. The sums of squares and products within areas were then obtained by computing the differences between the total sums and the between area sums.

The mean yield from the 2,451 fields studied was 10.2 bushels of wheat per acre (Table 3). The mean moisture depth at seeding time on these same fields was 25.6 inches. The linear regression coefficient of yield on moisture within areas was .2521 which was obtained from the equation $\frac{Sxy}{Sx^2} = \frac{105926.97}{420177.83} = .2521$; indicating a deviation from the mean yield of approximately one-fourth bushel for each inch deviation in moisture depth from the mean moisture depth. The regression line for yield on depth of moisture at seeding time is presented graphically in Fig. 1.

By classifying the data by years it was found that the mean yields were 9.8 bushels, 7.1 bushels and 11.7 bushels respectively. The mean moisture depth at seeding in 1936 was 18.8 inches, in 1937 was 25.7 inches and in 1938 was 26.3 inches. Therefore, on the basis of the relationship between depth of moisture and yield of wheat, the 1937 and

Table 6. Sums of squares and products for three years' data (1936-37-38).

df*		Sx^2	Sx_1^2	Sy^2	Sxy	Sx_1y	Sxx_1
2450	Total	447701	41571.61	157702.51	124965.80	27503.21	-20995.32
7	Area means	27523.17	17254.97	29876.86	19038.83	13527.49	17227.97
2443	Within areas	420177.83	24316.64	127825.65	105926.97	13975.72	38223.31

* df = degrees of freedom

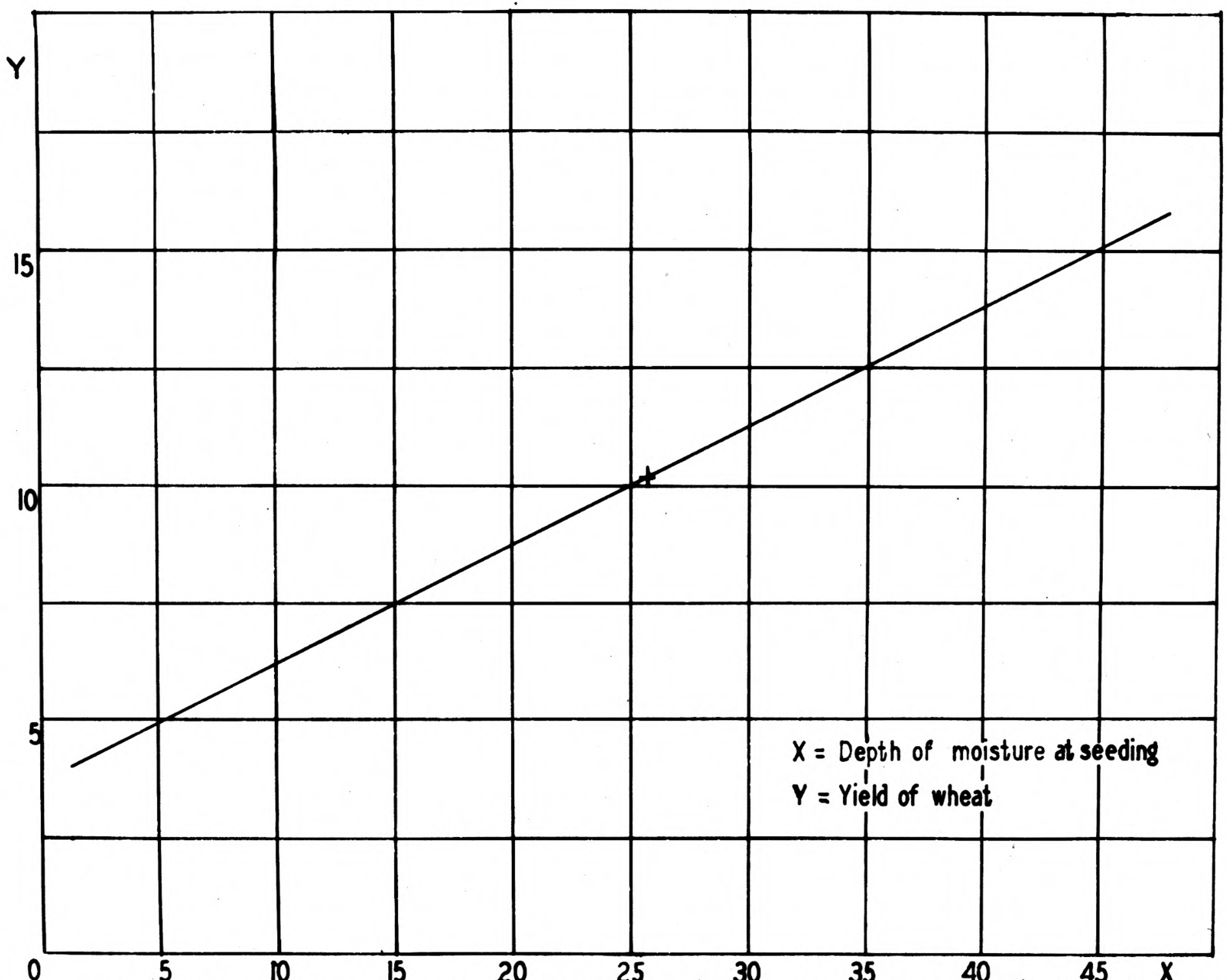

Fig. 1. The average relationship of wheat yield (bu.) to moisture depth (in.) at seeding time.

1938 yields should have been very similar, and both should have been higher than 1936. The fact that such was not the case seemed to indicate that some factor other than moisture in the soil at seeding time, profoundly influenced the yields.

A study similar to that made of the total data was then applied to each crop year. Sums of squares and products for separate years have been recorded in Table 7.

Linear regression coefficients, $\left(\frac{Sxy}{Sx^2}\right)$, of yield on depth of moisture within areas, computed for individual years, were found to be .3991, .2911, and .2320 respectively. After plotting separate regression lines for the three years studied upon a single graph (Fig. 2), it was observed that although the mean yields varied widely the increases in yield for each additional inch of moisture depth, within given years, were quite similar.

For further comparison, the annual mean yields were superimposed upon the grand mean for all years and regression lines plotted in terms of deviation from the mean (Fig. 3).

The linear relationship of depth of moisture at seeding time to yield of wheat within type-of-farming areas was also studied from the standpoint of the regression each year and the total regression for all years. Regression coefficients

Table 7. Sums of squares and products for individual years.

Year	df*	Source	Sx^2	Sx_1^2	Sy^2	Sxy	Sx_1y	Sxx_1
1936	177	Total	24001.25	1462.54	11415.12	10515.09	224.64	48.51
	6	Area means	2271.24	223.72	3219.84	1841.67	-2.78	-161.69
	171	Within areas	21730.01	1238.82	8195.28	8673.42	227.42	210.20
1937	700	Total	135899.71	2421.64	42575.58	43860.86	4652.88	3471.73
	7	Area means	9083.34	1983.57	10585.66	6944.22	4030.52	3075.91
	693	Within areas	126816.37	438.07	31989.92	36916.64	622.36	395.82
1938	1571	Total	278784.48	15761.71	93319.13	68660.07	7577.48	-28396.77
	7	Area means	21983.71	11406.20	19483.60	9090.48	83673.25	21038.24
	1564	Within areas	256800.77	4355.51	73835.53	59569.59	-76095.77	49435.01

* Degrees of freedom

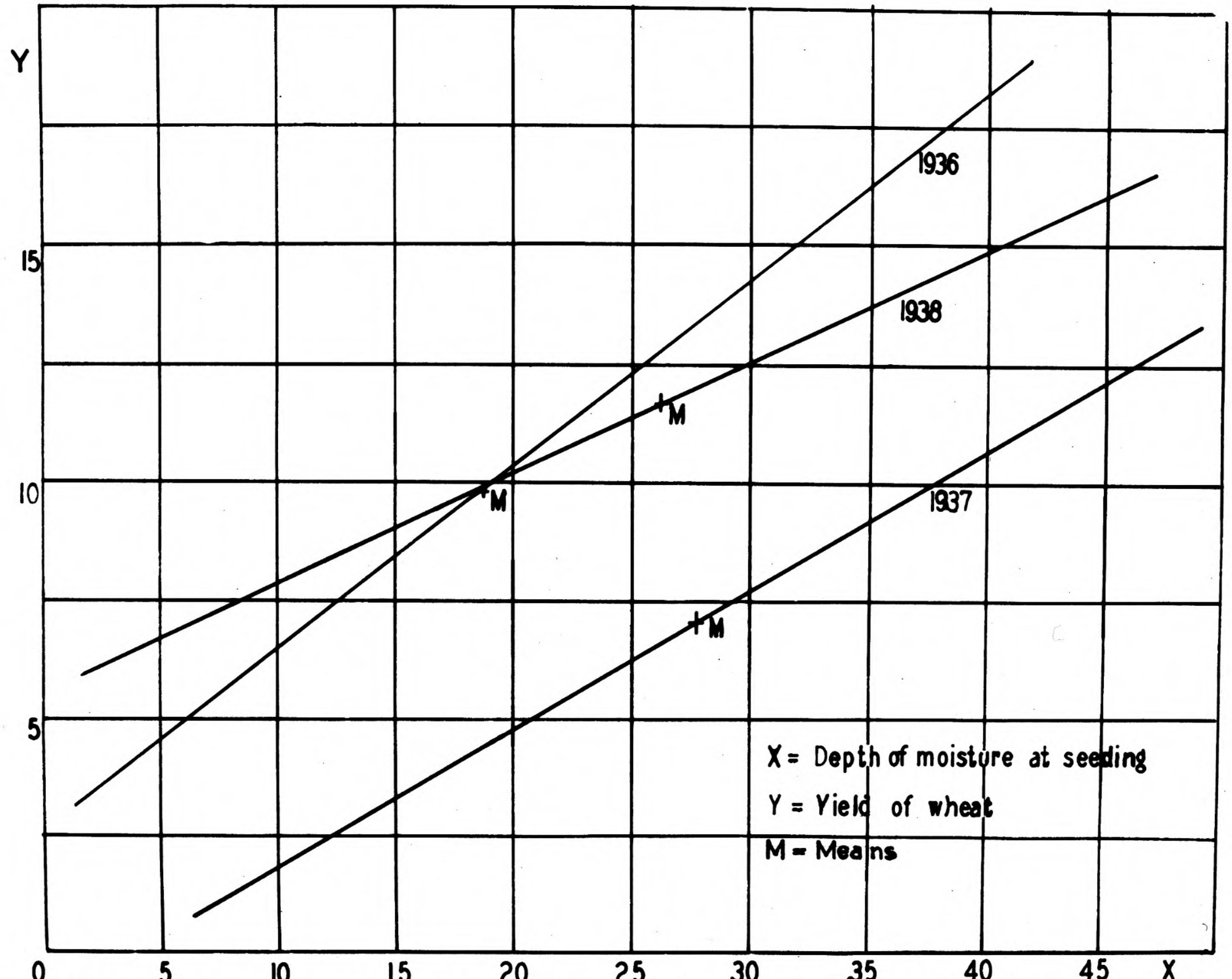

Fig. 2. The annual relationships of wheat yield (bu.) to moisture depth (in.) at seeding time.

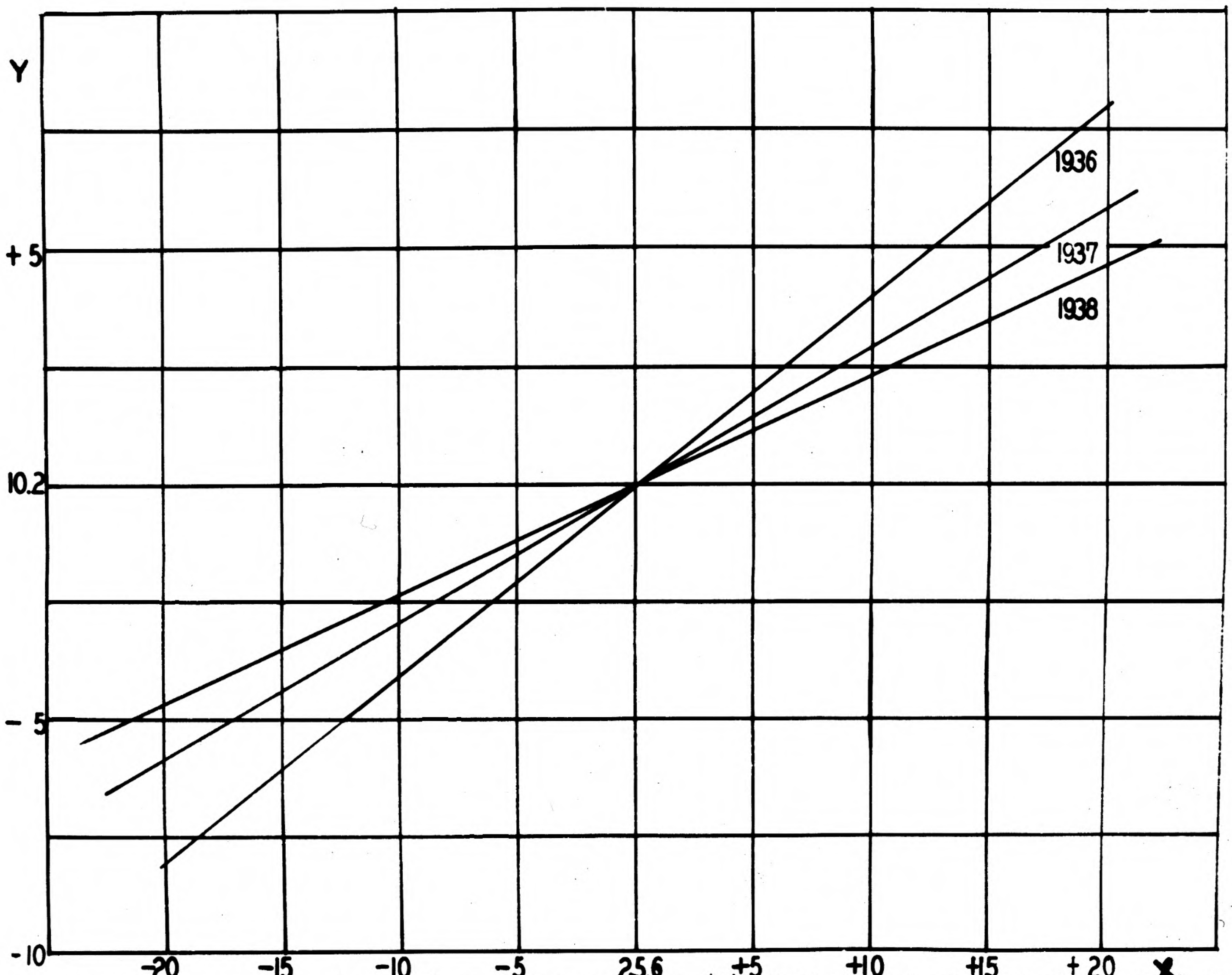

Fig. 3. Annual regressions yield (Y) on moisture depth (X) plotted as deviations from grand means.

were computed and recorded in Table 8. Since the methods of analysis were essentially similar to those used previously the mathematical details have been omitted.

Table 8. Coefficients of regression of yield upon depth of moisture for each type-of-farming area each year and all years.

Area	1936	1937	1938	1936-37-38
7	.4682	.3145	.0387	.1316
8		.4092	.1761	.2523
9	.4797	.4507	.2087	.2892
10a	-.0995	.2863	.2629	.2555
10b	.2792	.1896	.2082	.1932
10c	.4876	.3202	.2823	.2971
11	.5001	.3661	.2934	.3053
12	.5089	.1944	.1911	.2179

Not only was there a rather broad variation between the relationship of depth of moisture to wheat yield in differen years but the effect of depth of moisture varied between areas in the same year.

The Effect of Rainfall During the Growing Period Upon the Yield of Wheat

Preliminary observations of the effect of rainfall, October 1 to May 31, upon the yield of wheat harvested, indicated almost no relationship between these two variables.

The three-year average rainfall for the period was 10.22 inches and the average yield of wheat 10.2 bushels per acre. In 1936 there was an average of 8.69 inches of precipitation during the wheat growing period for the 20 counties in the 7 areas studied. The average wheat yield per acre was 9.8 bushels. In 1937, 38 counties were studied in 8 type-of-farming areas. The average precipitation for the period October 1 to May 31 was 5.74 inches and the average yield of wheat was 7.1 bushels. Similar averages from 41 counties in 8 areas in 1938 were 12.40 inches of precipitation and 11.7 bushels of wheat per acre. The rank of the annual average yields corresponded to the rank of the average seasonal rainfall values but the regression coefficients for yield on rainfall were widely different for the three years, being .1836 in 1936; 1.1924 in 1937; and -.0005 in 1938.

The coefficient of regression for yield upon rainfall, all fields all years was .5747 but the coefficients for individual areas, all years, varied from .0485 in area 7 to .8902 in area 12, as shown in Table 9.

Table 9. Coefficient of regression of yield upon rainfall for each type-of-farming area and for all areas (1936-37-38).

Area	Regression coefficient
7	.0485
8	.6213
9	.1668
10a	.3356
10b	.6529
10c	.6269
11	.6856
12	.8902
All areas	.5747

The Combined Effects of Depth of Soil Moisture at Wheat Seeding Time and Rainfall October 1 to May 31 Upon the Yield of Wheat

Although each of the factors, depth of moisture at seeding time and rainfall during the growing period, seemed to be related to the yield of wheat in western Kansas, the variability of the influence of each factor indicated either that there were other influences which could not be ignored or that the two influences, depth of moisture and rainfall during the growing season, were interrelated factors.

The annual averages for depth of moisture at seeding time, rainfall during the growing period and yield of wheat have been recorded in Table 10.

Table 10. Averages of depth of moisture at seeding time, rainfall during the growing period and yield of wheat for 1936, 1937, and 1938.

Year	Average depth of moisture	Average precipitation Oct. 1 to May 31	Average yield of wheat
	Inches	Inches	Bushels
1936	18.8	8.69	9.8
1937	25.7	5.74	7.1
1938	26.3	12.40	11.7
3-year average	25.6	10.22	10.2

From the data in Table 10, it was noted that although the soil was wet to a greater average depth in 1937 than in 1936, average rainfall during the growing season was definitely less in 1937 than in 1936, and the average yield of wheat was lower.

Nineteen thirty-eight had the advantage over the other two years in depth of moisture, rainfall, and yield.

The simultaneous consideration of the effects of both depth of moisture at time of seeding and rainfall during the growing period made the problem one of multiple regression.

Using Snedecor's (1937) alternative method, coefficients were computed directly from the sums of squares and products in Table 6. The symbols, bx and bx_1 were used to represent partial regression coefficients of yield on depth of moisture and yield on rainfall, respectively. Thus:

$$bx = \frac{(Sxy)\ (Sx_1{}^2) - (Sx_1y)\ (Sxx_1)}{(Sx^2)(Sx_1{}^2) - (Sxx_1)^2}$$

$$= \frac{(105926.97)(24316.64) - (13975.72)(-38223.31)}{(420177.83)(24316.64) - (-38223.31)^2}$$

$$= \frac{2,575,787,996 + 534,198,697}{10,217,313,028.09 - 1,461,023,720.76}$$

$$= \frac{3,109,986,693}{8,756,289,307}$$

$$= .3552$$

and

$$bx_1 = \frac{(Sx_1y)(Sx^2) - (Sxy)(Sxx_1)}{(Sx^2)(Sx_1{}^2) - (Sxx_1)^2}$$

$$= \frac{(13975.72)(420177.83) - (105926.97)(-38223.31)}{(420177.83)(24316.64) - (-38223.31)^2}$$

$$= \frac{5872287702 + 4048882589}{10217313038.09 - 1461023720.76}$$

$$= \frac{9921170291}{8756289307}$$

$$= 1.1330$$

Therefore, when the variability due to differences in rainfall was removed, the linear relationship of yield to depth of moisture could be expressed with the partial regression coefficient .3552 and likewise when depth of moisture was held constant, the partial regression coefficient of yield on rainfall became 1.1330.

The variance of yield was analyzed and the analyses described in Table 11.

According to the analysis of variance of wheat yield, a highly significant relationship existed between depth of moisture and yield when the effect of rainfall was held constant, as is shown by the F value, 651. Likewise, the effect of rainfall was even more significant (F = 879) than moisture depth when the latter was held constant. However, the significance of the combined effect of the two factors was greater by far than the significance of either taken independently, as shown by the F value 8764.

By letting $\overline{Y}$, $\overline{X}$ and $\overline{X}_1$ represent the means of yield, depth of moisture at seeding time and rainfall, October 1 to May 31, respectively, for the 2,451 fields studied, also bx and bx_1 represent partial regression coefficients of yield on moisture depth and yield on rainfall, a multiple regression equation was constructed as follows:

$$\text{Estimate of yield} = \overline{Y} + bx(X - \overline{X}) + bx_1\,(X_1 - \overline{X}_1)$$
$$= 10.2 + bx(X - 25.6) + bx_1\,(X_1 - 10.22)$$
$$= 10.2 + .3552(X - 25.6) + 1.133(X_1 - 10.22)$$
$$= 10.2 + .3552X - 9.09312 + 1.133X_1 - 11.57926$$
$$= .3552X + 1.133X_1 - 10.5$$

The standard error of estimate was found to be 5.5 bushels indicating that an average of four out of six yields

Table 11. The analyses of variance of wheat yields.

Source	Degrees of freedom	Formula	Sum of squares $(SY)^2$	Mean square $\frac{Sy^2}{df}$	F
Within areas	2443		127825.65	52323	
Reduction due to regression on moisture plus rainfall	2	$bx\ S(xy) + bx_1\ S(X_1Y) = (.3552)(105926.97) + (1.133)(13975.72)$	53459.75	26729.88	8764
Residual error of prediction	2441	127825.65 - 53459.75	7436.59	3.05	
Reduction due to regression on moisture alone	1	$\frac{[S(XY)]^2}{SX^2} = \frac{(105926.97)^2}{420177.83}$	26704	26704	651
Remainder	2442	127825.65 - 26704	101121.65	41.41	
Hence by subtraction, reduction due to regression on rainfall after fitting regression on moisture	1	53459.75 - 26704	26755.75	26755.75	879
Remainder	2442	127825.65 - 26755.75	73365.90	30.45	

would fall within 5.5 bushels of the mean yield, one out of six would exceed the mean by more than 5.5 bushels, and one out of six would be less than the mean yield by more than 5.5 bushels.

The multiple regression coefficient of .64, calculated for 2448 degrees of freedom, was highly significant (Snedecor, 1937).

The multiple regression equation, estimate of yield = $.3552X + 1.133X_1 - 10.5$, was applied to data for each type-of farming area and the estimated yields compared with the actual yields in Table 12. Seven of the eight estimates fell nearer than 5.0 bushels to the actual average yield for the respective area, the error in four areas being less than one bushel.

Table 12. Estimated yields, using multiple regression equation, compared to yields reported by farmers for type-of-farming areas.

Area	No. of fields	Moisture depth	Rainfall Oct. 1 to May 31	Yield per acre Reported	Yield per acre Estimated	Error
		Inches	Inches	Bushels	Bushels	Bushels
7	158	22.9	11.25	14.5	10.4	-4.1
8	66	20.3	10.22	13.0	8.3	-4.7
9	358	30.8	13.14	14.7	15.3	+ .6
10a	189	21.6	8.37	6.1	6.7	+ .6
10b	525	22.0	7.58	5.5	5.9	+ .4
10c	369	29.1	14.80	10.4	16.5	+6.1
11	553	26.3	9.10	12.5	9.2	-3.3
12	233	25.0	7.90	7.8	7.3	- .5
All areas	2451	25.6	10.22	10.2	10.2	----

The average yields per acre per year were also calculated. Estimates for 1936 and 1937 were lower than the actual averages and the estimate for 1938, slightly in excess of the actual average yield. Actual and estimated annual yields have been recorded in Table 13.

Table 13. Estimated yields of wheat, using multiple regression equation and yields reported by farmers (average of 1936-37-38).

Year	No. of fields	Reported yield	Estimated yield	Error
		Bushels	Bushels	Bushels
1936	178	9.8	6.0	-3.8
1937	701	7.1	5.1	-2.0
1938	1572	11.7	12.9	+1.2

Through the continued cooperation of county agricultural agents and interested wheat growers, data were obtained from 473 fields in 1939. In these fields the mean moisture depth at seeding time was 30.1 inches. Merely knowing the depth of moisture at seeding time and ignoring rainfall during the growing period, a simple regression equation of yield on moisture depth ($Y = .2521X + 3.77$) was first used to estimate the yield per acre. The estimated yield thus computed was 11.4 bushels per acre.

The average rainfall during the growing period was

6.47 inches (Flora, 1938-39) in the counties from which reports were received. Ignoring depth of moisture and applying a regression equation for yield on rainfall, ($Y = .5747X_1 + 4.33$) resulted in an estimated average yield of 8.05 bushels per acre.

However, when both factors were taken into account by the use of the multiple regression equation (Estimate of yield $= .3552X + 1.133X_1 - 10.5$) the estimated yield was computed to be 7.52 bushels. The actual average yield, as reported for the 473 fields, was 6.8 bushels of wheat per acre.

Table 14 shows the averages of depth of moisture and rainfall during the growing season and the estimates of yield of wheat compared with the reported yields in 1939. Estimates computed for each of 18 counties and for the total of the 18 counties were based upon depth of moisture at seeding time, upon rainfall during the growing period and upon the combined factors, depth of moisture and rainfall.

The combined effect of depth of moisture at seeding time and rainfall, October 1 to May 31 was expressed graphically in Fig. 4. With the effect of depth of moisture at seeding time held constant, the influence of rainfall during the growing period upon yield has been expressed by the partial regression coefficient 1.1330 and likewise with

Table 14. Average depth of moisture at time of seeding, average rainfall during the growing season and actual and estimated yields of wheat for 18 counties in 1939.

County	No. of fields	Depth of moisture	Rainfall Oct. 1 to May 31	Yield per acre	Estimate of yield based on: Moisture depth	Error	Rainfall	Error	Moisture depth + rainfall	Error
		Inches	Inches	Bus.	Bus.	Bus.	Bus.	Bus.	Bus.	Bus.
Comanche	55	37.7	6.66	9.0	13.3	+4.3	8.2	-0.8	10.4	+1.4
Decatur	20	32.8	4.98	6.2	12.0	+5.8	7.2	+1.0	6.8	+0.6
Grant	20	33.7	5.16	3.6	12.3	+8.7	7.3	+3.7	7.3	+3.7
Gray	10	22.0	6.15	3.1	9.3	+6.2	7.9	+4.8	4.3	+1.2
Hodgeman	14	33.9	5.92	1.2	12.3	+11.1	7.7	+6.5	8.2	+7.0
Kiowa	16	34.2	5.34	10.2	12.4	+2.2	7.4	-2.8	7.7	-2.5
Lane	22	22.7	5.59	1.7	9.5	+7.8	7.5	+5.8	3.9	+2.2
Logan	15	30.7	6.74	2.9	11.5	+8.6	8.2	+4.3	8.0	+5.1
Meade	51	30.3	7.54	4.8	11.4	+6.6	8.7	+3.9	8.8	+4.0
Pawnee	58	35.6	5.49	5.8	12.7	+6.9	7.5	+1.7	8.4	+2.6
Pratt	8	43.8	6.49	24.9	14.8	-10.1	8.1	-16.8	12.4	-12.5
Rawlins	35	38.4	7.10	10.6	13.5	+2.9	8.4	-2.2	11.2	+0.6
Rooks	25	21.0	7.56	5.4	9.1	+3.7	8.7	+3.3	5.5	+0.1
Rush	41	30.0	5.63	5.1	11.3	+6.2	7.6	+2.5	6.5	+1.4
Sheridan	11	36.7	9.45	12.8	13.0	+0.2	9.8	-3.0	13.2	+0.4
Stafford	25	34.7	6.01	18.3	12.5	-5.8	7.8	-10.5	8.6	-9.7
Stanton	18	35.6	6.95	4.7	12.7	+8.0	8.3	+3.6	10.0	+5.3
Stevens	29	26.4	8.16	2.7	10.4	+7.7	9.0	+6.3	8.1	+5.4
18 counties	473	30.1	6.47	6.8	11.4	+4.6	8.05	+1.25	7.5	+0.7

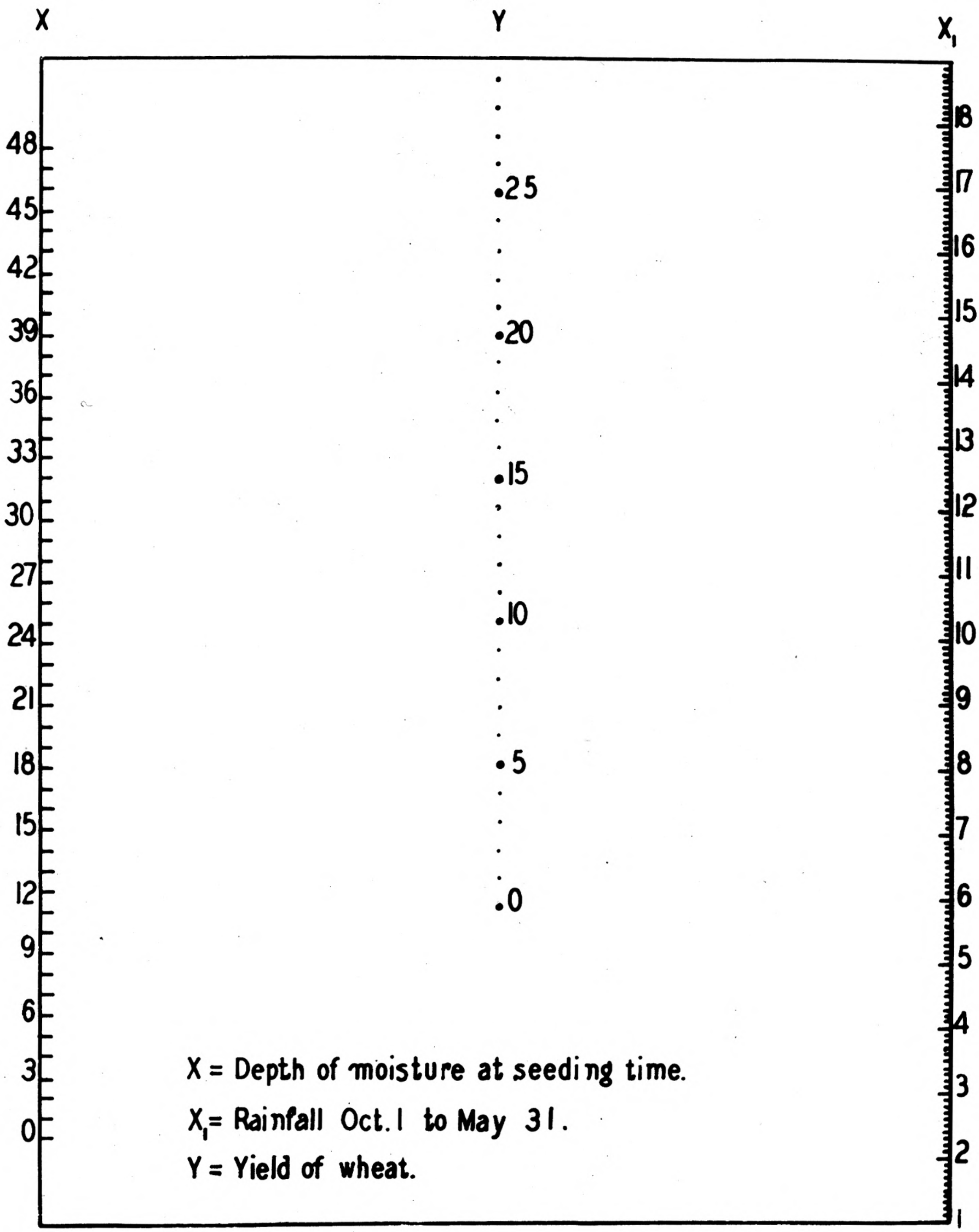

Fig. 4. The multiple regression equation, estimate of $Y = .3552X + 1.1330X_1 - 10.5$, presented graphically. A straight line between given values of X and X_1 will intersect the estimate of Y.

rainfall stabilized the influence of depth of moisture upon yield was found to be represented by the partial regression coefficient .3552. The ratio between these two coefficients $\frac{bx_1}{bx} = \frac{1.133}{.3552} = 3.19$ was found to be 3.19 to 1. In other words, each deviation of 1 inch in rainfall from the mean rainfall brought about a deviation in yield from the mean 3.19 times greater than a deviation in yield resulting from a deviation of 1 inch in moisture depth. Since one inch in moisture depth was only about one-third as effective as one inch of rainfall, one rainfall interval, in Fig. 4, was made to equal approximately three intervals of depth of moisture. Yield intervals were determined by actual computation of yields using the multiple regression equation, estimate of yield $= .3552X + 1.133X_1 - 10.5$.

Depth of moisture at seeding time (X) was scaled upon the left hand margin of Fig. 4, rainfall October 1 to May 31 upon the right and the estimated yield of wheat per acre (Y) up the center, parallel to and midway between the depth of moisture and rainfall axes. By placing one end of a straight edge at the point on the X scale, representing inches of moisture depth at seeding, and the other end at the point on the X_1 scale representing inches of rainfall, from October 1 to May 31, the estimated yield of wheat per acre may be read on the Y scale.

DISCUSSION

Relation of Depth of Soil Moisture at Seeding Time to Yield of Wheat

The results obtained from the preliminary study of 2,360 sets of paired field data for the harvest years 1936, 1937 and 1938 showed an average increase of approximately two bushels of wheat per acre for each increase of six inches in moisture depth at the time of seeding. If six inches of silt loam or silty clay loam soil will hold one inch of available water, as suggested by Burr (1914) and by Hallsted and Mathews (1936), then one inch of available water produced approximately two bushels of wheat. This relationship of available water to wheat yield is in excellent accord with the statement by Mathews and Brown (1938) that each half-inch of water in excess of 7.37 inches produced one bushel of wheat. Summer fallowing increased the yield of wheat approximately in proportion to the increase in moisture depth resulting from fallow. Fallowed soil that was dry at seeding time produced no greater yield, on the average, than continuously cropped soil that was dry when seeded. Likewise, soil wet at seeding time, even though having been cropped the previous year, yielded as satisfactorily as fallowed soil similarly wet. Therefore, it appears that water storage was the principal value of the fallow and that for the productivity level encountered in this experiment, fertility was not a determining factor in productivity.

The findings agreed fairly well with those of Hallsted and Mathews (1936) who pointed out that the results of tests conducted on the experiment stations at Hays, Colby, and Garden City indicated that the yield in 71 percent of the cases should be expected to be less than 5 bushels if the soil was dry at seeding time. In the 2,360 farm tests studied, 73 percent of the fields that were dry at seeding time failed to produce more than 5 bushels per acre. Furthermore, the prediction of Hallsted and Mathews (1936) based upon experiment station data was that if the soil was wet three feet or deeper, there existed only a 10 percent chance of harvesting less than five bushels per acre. In the farm fields studied, only 12 percent of those wet 31 inches or deeper at seeding time, produced less than five bushels per acre.

However, the depth of moisture at seeding time was found to be a more satisfactory means of predicting the chance for failure than for predicting yields other than failures. For example, according to Hallsted and Mathews (1936) when the soil was wet into the third foot at seeding, 6 percent of the yields on the experimental plots were between five and ten bushels per acre while in the farm tests studied, 22 percent of the fields wet 31 inches or deeper yielded between five and ten bushels of wheat per acre.

This situation which may have been influenced by a higher level of yields on experiment stations, would seem to substantiate the statement of Call and Hallsted (1915) that a certain amount of stored moisture did not insure a certain yield of wheat, the yield secured being quite as dependent upon the amount and distribution of rainfall during the growing season. Cole and Mathews (1923) observed a similar situation in connection with the growing of spring wheat and Mathews (1925) found it difficult to predict yields of spring wheat early in the season because rainfall during the growing period was seldom normal.

Furthermore, assuming that the findings of Burr (1914) and Hallsted and Mathews (1936) are essentially applicable to soils of the areas studied, then soil wet three feet deep would contain approximately 6 inches of available water, which is less than the 7.37 inch threshold said by Mathews and Brown (1938) to be necessary before any yield was produced.

A total of 2,451 fields were studied during the three years, 1936, 1937 and 1938. The mean moisture depth at seeding time was 25.6 inches and the mean yield 10.2 bushels of wheat per acre. The regression coefficient of yield on moisture depth was .2521, indicating a deviation from the mean yield of slightly more than one-fourth bushel for each inch deviation to moisture depth from the mean moisture depth. The linear regression equation for estimate of yield was, yield = .2521 times moisture depth + 3.77.

By separating the years and considering each independently, it was found that the mean moisture depths were 18.8 inches, 25.7 inches and 26.3 inches, respectively, and that the corresponding annual mean yields were 9.8 bushels, 7.1 bushels and 11.7 bushels. Thus, the means of years varied rather widely and although soil moisture conditions were more favorable for the 1937 crop than for the 1936 crop, the 1936 mean yield exceeded that of 1937 by 2.7 bushels per acre. There was, however, a fair similarity in the slopes of regression lines, the regression coefficients for the respective years being .3991, .2911 and .2320.

Not only was there a rather broad variation between the relationship of depth of moisture to wheat yield in different years but the effect of depth of moisture varied between type-of-farming areas (Throckmorton, Hodges, Pine, and Grimes, 1937) in the same year.

Consequently, while depth of moisture at seeding time was found to be an important factor to be considered in predicting wheat yields, or more accurately, wheat failures, in western Kansas, the variation between means of years and between type-of-farming areas seemed to indicate that there were other factors which should not be ignored.

The Effect of Rainfall During the Growing Period Upon the Yield of Wheat

According to Hallsted (1937) wheat yields in western Kansas have sometimes been reduced by factors such as insects and plant diseases, but over a period of years, moisture has been the limiting factor. Therefore, it appeared logical to take into account the effect of rainfall during the growing period upon the yield of wheat in addition to moisture depth at seeding. In this study, the wheat growing period was arbitrarily defined as the period October 1 to May 31. Such a definition, of course, introduced some error because of the possibility that rain fell after the date of seeding and before October 1 and because May 31 does not ordinarily mark the end of the actual growing season. However, if a growing wheat crop is doomed to failure there is some advantage in recognizing that situation early in the spring. Rainfall information was obtained from reports of the United States Weather Bureau. (Flora, 1935, 1936, 1937 and 1938). Here again some error was inevitable because the position of the official weather observation was not necessarily near the fields studied. But, inaccurate as the method of sampling may have been, significant changes in the relationship of the variables were observed when the effect of rainfall was injected into the problem.

The three-year average rainfall for the period was 10.22 inches and the average yield of wheat, 10.2 bushels per acre. The coefficient of regression of yield on rainfall was .5747 indicating a deviation from the mean yield of over .57 bushel of wheat for each inch deviation in rainfall. The linear regression equation of estimate was, Y = .5747 times rainfall + 4.33.

When the individual years were studied with regard to the relationship between rainfall and wheat yield, as was done with depth of moisture and wheat yield, it was observed that in 1936 there was an average of 8.69 inches of precipitation during the wheat growing period, whereas in 1937 the average for the areas studied was 5.74 inches. Nineteen thirty-eight was the wettest season, with 12.4 inches of precipitation during the growing period. It will be recalled that yields for the three years were 9.8 bushels, 7.1 bushels and 11.7 bushels, respectively, and that moisture had penetrated deeper into the soil in 1937 than in 1936;

1937 and 1938 being practically equal in that respect. So, although moisture was deeper in the soil in 1937 than in 1936, rainfall during the growing season was nearly 3 inches less in 1937 and consequently lower yields of wheat were harvested.

Nineteen thirty-eight was highest in all three factors; depth of moisture, rainfall and yield.

Although the rank of the annual average yields corresponded to the rank of the average seasonal rainfall values, the regression coefficients for yield on rainfall were widely different, being .1836 in 1936; 1.1924 in 1937 and .0005 in 1938. Thus, there were increases in yield for increases in rainfall in 1936 and 1937 but in 1938 the average rainfall (12.4 inches) received between October 1 and May 31 was practically optimum for wheat development and increases above that average were actually detrimental to the yield. This situation was especially obvious in Ellis, Barton and neighboring counties where damage from lodging and rust was common.

Regression coefficients of yield upon rainfall for individual areas, all years, ranged from .0485 to .8902 with the greatest tendency toward increases in yield from additional rainfall occurring in the far western counties where deficiencies in moisture for crop production were most prevalent. This tendency would seem to agree with the statement of Alsberg and Griffing (1928) that with increasing increments the effects become larger and then decrease until near the optimum they exert little effect and with Henney (1932) who suggested that different parts of Kansas would need separate, individual estimating equations.

The Combined Effect of Depth of Soil Moisture at Seeding Time and Rainfall During the Growing Period upon the Yield of Wheat

A multiple regression equation (Snedecor, 1937) was computed using depth of moisture at seeding time, rainfall during the growing period and wheat yield for 1936, 1937 and 1938 as the variables. The equation of estimate constructed was, estimate of yield = .3552 times depth of moisture at seeding time + 1.133 times rainfall, October 1 to May 31 - 10.5. The standard error of estimate was found to be 5.5 for an individual field and the multiple correlation coefficient .64. The standard error was rather high and the multiple correlation coefficient rather low. However, in view of the large number of fields studied (2,451) the coefficient of correlation was highly significant and the equation of estimate, because of its simplicity, may perhaps be of some practical value in estimating the yield of a field and of greater value when applied to a region that has been adequately sampled with respect to depth of moisture at seeding time and subsequent rainfall.

Mathews and Brown (1938) recognized the desirability of combining the two factors, soil moisture at seeding time and rainfall during the growing period, but transposed soil moisture into inches of water to which they added rainfall and expressed the combined factor as total water used, thus estimating the yield of wheat with the equation, yield = $\frac{\text{water used} - 7.37}{0.51}$.

Since the semi-technical ability and equipment necessary to determine the amount of water the soil contains, are beyond the reach of many farmers, it seemed desirable to construct a simple formula or equation of estimate of wheat yield based upon more easily determinable factors.

Data were obtained from 473 fields in 1939. In these fields the mean moisture depth at seeding time was 30.1 inches, mean rainfall October 1 to May 31 was 6.47 inches and the mean yield 6.8 bushels per acre. The estimated yield, based upon depth of moisture alone was 11.3 bushels per acre. Based upon rainfall it became 8.05 bushels but when calculated with the multiple regression equation, the estimated yield was 7.5 bushels per acre. Thus, when the three equations of estimate were used with independent data for 1939, rainfall during the growing period was found to be a more accurate measure of yield than depth of moisture at seeding time but an estimate based upon the combined effect of the two factors was better than when either depth of moisture or rainfall was used separately.

The graph (Fig. 4) developed from the multiple regression equation may be used to quickly determine an estimate of yield without solving the equation. It will be noted that this graph provides for a minimum or threshold of water use, the zero point on the yield axis being above the zero of moisture depth and rainfall to the extent of about 8 inches of water. This agrees rather well with statements by Cole and Mathews (1923), Alsberg and Griffing (1928), and with Mathews and Brown (1938) who found that an average minimum of 7.37 inches of water were necessary before any yield would be produced at the Colby and Garden City experiment stations.

By determining the depth to which the soil is wet at seeding time, anyone possessing some knowledge as to expected rainfall during the growing period may estimate the probable yield either by solving the prediction equation or by using the graph. Furthermore, by determining the moisture depth at seeding time, it is possible to quickly estimate the amount of rainfall necessary for the production of any desired yield per acre.

Although 2,451 samples were included in the data studied, it must be remembered that only three crop years were covered. Furthermore, two of the three years studied were exceptionally dry. Consequently, the relationship of the variables is probably not strictly linear and predictions based upon the equation computed may be expected to be less accurate than will be the case after additional years of work have been included.

SUMMARY AND CONCLUSIONS

Conclusions based upon the study of the relationship of depth of moisture at seeding time and rainfall during the growing period to yield of wheat are:

1. In the three years studied, depth of soil moisture at seeding time was an important factor to be considered in predicting probable wheat yields on western Kansas farms. A dry soil at seeding time was nearly always associated with crop failure.

2. Rainfall during the growing period was rather closely associated with average wheat yields but the influence of rainfall upon yield was obviously interrelated with the influence of depth of moisture at seeding time upon yield.

3. Depth of moisture at seeding time and rainfall during the growing period are easily determinable factors whose

multiple relationship to wheat yield during the three-years studied was expressed by the equation, estimate of yield = $.3552X + 1.133X_1 - 10.5$. (X = depth of moisture, X_1 = rainfall Oct. 1 to May 31).

4. A graph or chart was constructed with which it is possible to estimate the yield of wheat from the two factors, soil moisture depth at seeding time and rainfall during the growing period, without solving the equation of estimate.

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